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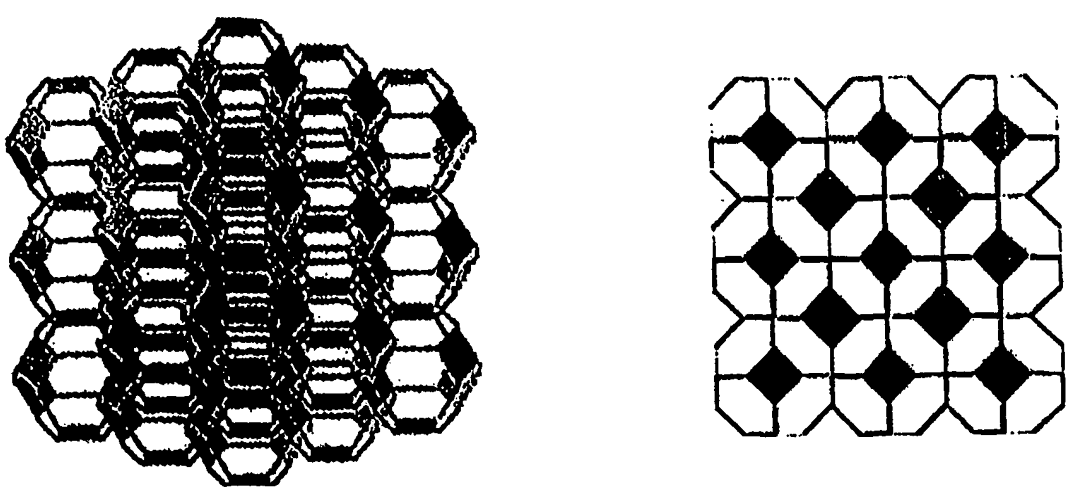


(a) (b)

(57) Abstract

A foam structure comprising a scaffold material including a predetermined repeating arrangement of polyhedral modules may have shapes of truncated octahedra, Kelvin minimal surface tetrakaidecahedra, or other polyhedral shapes. The foam may be open–cell, in which the polyhedral modules are formed of elongated members defining their edges, or closed–cell, in which the polyhedral modules are formed of substantially planar members defining their faces. The foam can be formed by computer–aided manufacturing techniques, self–assembly techniques, or lost core molding techniques. With this arrangement, a variety of idealized foam material shapes and sizes can be provided, for use in a variety of applications. In addition, the foam material can be designed to be multi–functional and to provide mechanical load–bearing along with other desired properties as required.

FOAM SCAFFOLD MATERIALS

Field of Invention

This application pertains to the construction and use of foam scaffold materials based on repeating arrays of polyhedra.

Background of the Invention

Hardened foams are common materials for certain applications, where high porosity is desired without sacrificing too much mechanical strength. The mechanical properties of such foams have been found to be somewhat difficult to predict and control precisely, however, in part because it is impossible to achieve perfect control over the size and shape of individual bubbles of the foam. The problem of discovering the lowest-energy configuration for a soap froth or other foam has been studied for more than a hundred years.

In 1887, Thomson (lord Kelvin) published his discovery of the minimal tetrakaidecahedron, which is believed to be the minimum surface area shape which tessellates in three-dimensional space (this shape tessellates on a body-centered cubic lattice). This shape represents an ideal form of a bubble in a dry, perfectly monodisperse foam.

Kelvin's minimal tetrakaidecahedron is a slightly distorted version of the orthic tetrakaidecahedron, which is obtained by truncating the six corners of a regular octahedron each to such a depth as to reduce its eight original (equilateral triangular) faces to equilateral equiangular hexagons. The orthic tetrakaidecahedron has six square faces and eight hexagonal faces. The Kelvin tetrakaidecahedron has curved edges, such that the "square" faces are planar and of slightly greater surface area than a true square, while the "hexagonal" faces are slightly nonplanar and of somewhat less surface area than a true hexagon. The exact shape and morphological parameters of the Kelvin tetrakaidecahedron are computed in Princen, *et al*, "The Surface Area of Kelvin's Minimal Tetrakaidecahedron: The Ideal Foam Cell," *J. Colloid and Interface Sci.*, Vol. 120(1), pp. 172-175, 1987 which is incorporated herein by reference. This polyhedron satisfies Plateau's conditions for a network of foam films; *i.e.*, three films meet along an edge at angles of 120°, while four edges meet in each corner at tetrahedral angles of 109.47°. Its surface area is 9.7% greater than the surface area of a sphere of the same volume.

Recently, other idealized foam arrangements which satisfy Plateau's conditions and have even lower surface areas than the Kelvin tetrakaidecahedron have been found. These arrangements comprise multiple polyhedra in each unit cell of a repeating lattice; the Kelvin tetrakaidecahedron is still believed to be the minimal surface area single polyhedron which can tessellate to fill space. One example of another foam arrangement is the Weaire-Phelan foam, described in Weaire *et al, Phil. Mag. Lett.* Vol. 69(2), pp. 107-110, incorporated herein by reference. The unit cell of this foam comprises six tetrakaidecahedra and two dodecahedra, and is arranged in a simple cubic lattice.

Networks or lattices of essentially one-dimensional members (open-cell foams) or essentially two-dimensional members (closed-cell foams) are expected to have the minimal mass necessary to enclose a given volume when Plateau's conditions are satisfied (see, for example, Gibson *et al* Cellular Solids: Structure & Properties, Pergamon Press, 1988), and thus are expected to exhibit an extremely high structural efficiency (high strength per unit mass). This property has been exploited in the construction of strong, porous materials. According to this method, a foam is created, for example by incorporating a large volume of a gas into a liquid, and then the foam is hardened. Since the liquid foam spontaneously attempts to satisfy Plateau's conditions in order too minimize its surface area, the hardened solid foam also satisfies these criteria. While materials having rather high-specific strengths have been made according to this technique (using either open- or closed-cell foams), their properties are usually nonoptimal, because it has been found to be impossible to form a truly monodisperse precursor foam before hardening (see, for example, D'Arcy Thompson, On Growth and Form, Revised edition, D'Arcy W. Thompson, Cambridge U. Press, 1942 (reprinted 1992) and Stevens, Patterns in Nature, Little Brown & Co., Boston, 1974). Further, there are definite bounds on the cell sizes and porosities achievable by these methods, which depend on the viscosities and surface energies of the material used to form the precursor foam. For example, polyurethane foams can be easily made only with cell sizes on the order of 100 μm-1m.

A perfectly monodisperse open- or closed-cell foam would be expected to have a very high specific strength. This configuration should be a very efficient way of using a minimum amount of material to support a load; it thus has applications when light weight and/or high porosity are desired in a structural material. There is also a need in many industrial applications, such as construction of airplane wings, where foams with unit volumes larger

than 1 cm^3 and covered by curved solid face plates that are integrally connected to surfaces of the foam may be particularly useful as replacements for light weight honeycomb panels. Unfortunately, no method currently exists for manufacturing a unitary material containing a monodisperse foam that can be fabricated in a wide range of sizes.

Summary of Invention

It is an object of this invention to provide a foam structure. This structure can be used for many applications where a lightweight, porous, strong structure is desired: for example, sporting equipment, such as skis, shin guards, helmets, and sneaker soles, boat fenders, airplane wings, insulation materials, shock and vibration absorbers, sound absorbers, and building materials.

In one aspect, the invention comprises a scaffold material, composed of an arrangement of integrally connected polyhedral modules arranged in a repeating pattern. Each polyhedral module includes a plurality of integrally connected structural members, wherein each polyhedral module has an edge length in the range of 10^{-9} m to 1 m.

In one embodiment of the scaffold material of the invention, the modules are composed of elongated members defining the edges of a polyhedron. In this embodiment, where the polyhedra have constant volume and satisfy Plateau's conditions, the scaffold material provides an idealized monodisperse open-cell foam with edges arranged geodesically (following minimal distance paths). The elongated members may be non-compressible and/or extensible, and may comprise linear, curvilinear, helical, spring, sawtooth form, crenulated, or entanglement elements. The polyhedral modules may also have edge lengths in the range of 10^{-6} m to $5x10^{-1}$ m, and preferably in the range of 10^{-5} m to 10^{-1} m.

In another embodiment of the scaffold material of the invention, the polyhedral modules include approximately planar members defining the faces of a polyhedron. In this embodiment, where the polyhedra have constant volume and satisfy Plateau's conditions, the scaffold material provides an idealized monodisperse closed-cell foam. The elongated members of this embodiment may be compressible and/or extensible. The polyhedral modules of this embodiment may also have edge lengths in the range of 10^{-6} m to $5x10^{-1}$ m, and preferably in the range of 10^{-5} m to 10^{-1} m.

In either of the above two embodiments of the scaffold material, the elongated members forming the polyhedral modules may be made of a number of materials, including

polyacrylates, polyepoxides, polyesters, polyurethanes, poly(methacryllic acid), poly(acrylic acid), polyimides, polysiloxanes, poly(glycolic acid), poly(lactic acid), polyamides, metals, glasses, ceramics, carbon, proteins, carbohydrates, nucleic acids, and lipids.

In addition, computer-aided manufacturing techniques such as stereolithography, micromolding, three dimensional microprinting, three dimensional laser-based drilling or etching, self-assembly techniques, sintering, fused deposition modeling, and lost core methods may be used to form the scaffolds.

Further, for either of the above scaffold materials, the polyhedra may be Kelvin tetrakaidecahedra, orthic tetrakaidecahedral, or other shapes, such as for example, the tetrakaidecahedra and dodecahedra of the Weaire-Phelan foam. In addition, adjacent modules may have members in common such as elongated members defining common edges in the open-cell configuration, and the substantially planar members defining common faces in the closed-cell configuration.

In another aspect of the invention, the above-described scaffold materials can be used in a method of manufacturing a mold. The method includes a step of providing a pattern in the shape of an article to be manufactured with the mold. This pattern includes a scaffold material that can be either of the above-described scaffold materials, or a hybrid mixture of the above-described scaffold materials. The pattern is then coated with a hardenable material and the hardenable material is transformed into a hard shell mold. The pattern is then removed from the hard shell mold to provide the mold.

The hard shell mold may then be used, for example, with an additional step of providing a flowable material into the hard shell mold and cooling the flowable material. The hard shell mold can then be removed by a number of techniques, to provide the article of manufacture. In certain embodiments, the pattern further includes a solid outer surface that surrounds the scaffold material.

As used herein, the term "tetrakaidecahedron" refers to a three-dimensional shape having fourteen sides consisting of polygons or distorted polygons (which may be nonplanar), and "dodecahedron" refers to a three-dimensional shape having twelve sides consisting of polygons or distorted polygons.

As used herein, the term "Kelvin tetrakaidecahedron" refers to the minimal tetrakaidecahedron described in Princen, *et al*, "The Surface Area of Kelvin's Minimal Tetrakaidecahedron: The Ideal Foam Cell," *J. Colloid and Interface Sci.*, Vol. 120(1), pp.

172-175, 1987 and illustrated in Figure 1b. In the ultimate minimal tetrakaidecahedron, the corners (*and thus the volume*) of the orthic polyhedron maintained. The quadrilateral faces remain planar but acquire bowed-out noncircular edges, each having a total turning angle of 109.47°-90°=19.47°. The corners of each nonplanar, wavy hexagon are still in one plane, while the hexagon contains three (and only three) straight lines, namely its three long diagonals.

As used herein, the term "orthic tetrakaidecahedron" refers to a straight-edged tetrakaidecahedron having six square faces and eight regular hexagonal faces; this shape is also described in the same reference and illustrated in Figure 1a or orthic tetrakaidecahedron (Fig. 1) which, in turn, is obtained by "truncating the six corners of a regular octahedron each to such a depth as to reduce its eight original (equilateral triangular) faces to equilateral equiangular hexagons".

As used herein, the term "Weaire-Phelan foam" refers to the arrangement of tetrakaidecahedrons and dodecahedrons described in Weaire *et al, Phil. Mag. Lett.* Vol. 69(2), pp. 107-110. In particular, the unit cell of this foam includes six tetrakaidecahedra and two dodecahedra, and is arranged in a simple cubic lattice.

As used herein, an "integrally connected" structure is one which is formed as a unitary piece, rather than one assembled from component parts via adhesive, welding, or other connective methods. An integrally connected structure will usually consist of a single material, but may comprise multiple materials when created by certain methods, such as fused deposition modeling or three-dimensional microprinting.

As used herein, a "module" is a plurality of integrally connected structure members that delineate the edges of at least a portion of a polyhedron.

As used herein, a "scaffold" is a material having an extended repeating structure, which forms a framework or skeleton onto which and into which additional components may be introduced to impart additional features to the material.

As used herein, modules arranged "in a repeating pattern" are considered to exhibit at least local translational symmetry including at least two identical unit cells. A unit cell can include any number of polyhedral modules and the modules may have any polyhedral shape. For example, a unit cell can respectively include a single polyhedral module, or multiple polyhedral modules of the same shape, or multiple polyhedral modules of different shapes, or multiple polyhedral modules of the same shape but having a different size scale, or other

arrangements. Conventional foams do not exhibit the symmetry of a repeating pattern, since no two component bubbles of the foam have exactly the same shape and size.

As used herein, the term "tessellate" means to fill space in a repeating pattern. Polygons may tessellate in two-dimensional space, and polyhedra may tessellate in three-dimensional space.

As used herein, the term "extensible element" is an element that is capable of extension or an increase in the length of the member within a given range of movement in response to application of a tensile force to one or both ends of the member.

As used herein, the term "non-compressible element" refers to an element that is incapable of shortening along its length when compressive force are applied to one or both ends of the member. However, the non-compressible member may be able to buckle under compression, without shortening its length. A non-compressible member may or may not be able to extend in length when external tensile forces are applied to its ends. Such an extensible, non-compressible member would be able to withstand compression, but not tension.

As used herein, the term "substantially planar member" refers to a members that primarily lie in one plane, but may include portions that lie outside the plane. For example, the faces of the ultimate minimal tetrakaidecahedron described above are "substantially planar", though they include bowed-out edges.

Brief Description of the Drawings

Figs. 1a and 1b show the orthic tetrakaidecahedron and the Kelvin tetrakaidecahedron, respectively.

Figs. 2a and 2b show two views of an open-cell idealized foam comprising an array of Kelvin tetrakaidecahedra.

Figs. 3a and 3b show two views of a closed-cell idealized foam comprising an array of orthic tetrakaidecahedra.

Figs. 4a and 4b show two views of a hybrid idealized foam having both open and closed elements.

Fig. 5 shows the internal idealized foam structure of a pattern for investment casting.

Fig. 6 shows an octet truss structure.

Fig. 7 is a CAD drawing of a cylindrical unitary curved octet truss structure.

Fig. 8 illustrates a cylindrical unitary curved single-layer octet truss structure made of copper.

Fig. 9 illustrates a two-layered cylindrical unitary curved two-layer octet truss structure made of copper.

Figs. 10 and 10a respectively show a perspective and an inside view of an egg structure.

Figs. 11 and 11a respectively show a perspective and an inside view of a dome structure.

Fig. 12 shows a perspective view of a sphere structure.

Fig. 13 illustrates a mold for the production of the cylindrical truss structure of Figs. 8-9.

Detailed Description of the Invention

As used herein, the term "tetrakaidecahedron" refers to a three-dimensional shape having fourteen sides consisting of polygons or distorted polygons (which may be nonplanar), and "dodecahedron" refers to a three-dimensional shape having twelve sides consisting of polygons or distorted polygons.

As used herein, the term "Kelvin tetrakaidecahedron" refers to the minimal tetrakaidecahedron described in Princen, *et al*, "The Surface Area of Kelvin's Minimal Tetrakaidecahedron: The Ideal Foam Cell," *J. Colloid and Interface Sci.*, Vol. 120(1), pp. 172-175, 1987 and illustrated in Figure 1b. In the ultimate minimal tetrakaidecahedron, the corners (*and thus the volume*) of the orthic polyhedron maintained. The quadrilateral faces remain planar but acquire bowed-out noncircular edges, each having a total turning angle of 109.47°-90°=19.47°. The corners of each nonplanar, wavy hexagon are still in one plane, while the hexagon contains three (and only three) straight lines, namely its three long diagonals.

As used herein, the term "orthic tetrakaidecahedron" refers to a straight-edged tetrakaidecahedron having six square faces and eight regular hexagonal faces; this shape is also described in the same reference and illustrated in Figure 1a or orthic tetrakaidecahedron (Fig. 1) which, in turn, is obtained by "truncating the six corners of a regular octahedron each to such a depth as to reduce its eight original (equilateral triangular) faces to equilateral equiangular hexagons".

As used herein, the term "Weaire-Phelan foam" refers to the arrangement of tetrakaidecahedrons and dodecahedrons described in Weaire *et al, Phil. Mag. Lett.* Vol. 69(2), pp. 107-110. In particular, the unit cell of this foam includes six tetrakaidecahedra and two dodecahedra, and is arranged in a simple cubic lattice.

As used herein, an "integrally connected" structure is one which is formed as a unitary piece, rather than one assembled from component parts via adhesive, welding, or other connective methods. An integrally connected structure will usually consist of a single material, but may comprise multiple materials when created by certain methods, such as fused deposition modeling or three-dimensional microprinting.

As used herein, a "module" is a plurality of integrally connected structure members that delineate the edges of at least a portion of a polyhedron.

As used herein, a "scaffold" is a material having an extended repeating structure, which forms a framework or skeleton onto which and into which additional components may be introduced to impart additional features to the material.

As used herein, modules arranged "in a repeating pattern" are considered to exhibit at least local translational symmetry including at least two identical unit cells. A unit cell can include any number of polyhedral modules and the modules may have any polyhedral shape. For example, a unit cell can respectively include a single polyhedral module, or multiple polyhedral modules of the same shape, or multiple polyhedral modules of different shapes, or multiple polyhedral modules of the same shape but having a different size scale, or other arrangements. Conventional foams do not exhibit the symmetry of a repeating pattern, since no two component bubbles of the foam have exactly the same shape and size.

As used herein, the term "tessellate" means to fill space in a repeating pattern. Polygons may tessellate in two-dimensional space, and polyhedra may tessellate in three-dimensional space.

As used herein, the term "extensible element" is an element that is capable of extension or an increase in the length of the member within a given range of movement in response to application of a tensile force to one or both ends of the member.

As used herein, the term "non-compressible element" refers to an element that is incapable of shortening along its length when compressive force are applied to one or both ends of the member. However, the non-compressible member may be able to buckle under compression, without shortening its length. A non-compressible member may or may not be

able to extend in length when external tensile forces are applied to its ends. Such an extensible, non-compressible member would be able to withstand compression, but not tension.

As used herein, the term "substantially planar member" refers to a members that primarily lie in one plane, but may include portions that lie outside the plane. For example, the faces of the ultimate minimal tetrakaidecahedron described above are "substantially planar", though they include bowed-out edges.

According to the present invention, a scaffold material is composed of an arrangement of integrally connected polyhedral modules. The scaffold forms a framework or internal skeleton upon which or into which additional materials may be, optionally, introduced. The modules may be any geodesically delineated polyhedral structure or portion thereof. The module may be a fully geodesic polyhedron, such as a tetrahedron, or a more complicated omni-triangulated system, such as icosahedron (twenty sided polyhedron) or octahedron (eight sided polyhedron). Alternatively, the module may also contain non-triangular elements, such as square, pentagonal, hexagonal or octagonal facets. In other alternative embodiments, the module may be a more complicated polyhedron which itself can be further decomposed into simpler geodesic elements. For example, the module may comprise a half-dome, which itself may be comprised of tetrahedral, geodesic sub-modules. In certain embodiments, the members may form polyhedral modules with different shaped polygonal faces or only a subset of members mapping out geodesic lines. Certain preferred module arrangements are illustrated in Figs. 2-4, 6, 7, and 10-12 and described further below. In certain preferred embodiments, all of the modules of a foam structure have the same volume.

The modules are composed of integrally connected structural members which form at least a portion of a polyhedron. In one set of embodiments, the structural members are elongated members and each module is composed of a plurality of integrally connected elongated members. These embodiments, generally, are open-cell foam structures. In another set of embodiments, the structural members are substantially planar members and the scaffold material is composed of a plurality of integrally connected substantially planar members that define faces of the modules. These embodiments, generally, are closed-cell foam structures. In some embodiments of this set, neighboring polyhedral modules share members as common faces. In other embodiments, the scaffold material may be composed of integrally connected modules that include both integrally connected elongated members and integrally connected

substantially planar members to form hybrid foam structures having both closed-cell and open-cell elements. These hybird foams can be produced over a very wide range of tortuosities, by varying the ratio of closed to open cells. Such foams are difficult to construct using conventional techniques, and the tortuosity of the foam is very difficult to control. Any of the above-described foams may include a solid laminate layer integrally connected to a surface or separately connected to a surface (e.g. by fixing, adhering, welding, and the like), as described further below.

The structural members which comprise the modules are integral members of a single module, that is, they are not joined as separate elements but are formed as a unitary body. The structural members are of a dimension dictated by the intended application of the resultant scaffold material. The elongated members typically have a length in the range of 10^{-9} m to 1 m, more typically in the range of 10^{-6} m to 5×10^{-1} m, and more typically in the range of 10^{-5} m to 10^{-2} m. The planar members typically have edge lengths in the range of 10^{-9} m to 1 m, more typically 10^{-6} m to 5×10^{-1} m, and more typically in the range of 10^{-5} m to 10^{-2} m. Typically, the cross-sectional diameter of the elongated element is in the range of about 1-1000 μm and planar members have a cross-sectional thickness in the range of about 1-1000μm.

The structural members, and hence the scaffold material itself, may be prepared from any suitable material, dependent upon the desired application. For example, the scaffold may be prepared from non-erodible polymers such as, by way of example only, polyacrylates, epoxides, polyesters, polyurethanes, poly(methacrylate), polyimides, and polysiloxanes. Where flexibility is desired, such as when the structural members are extensible, the elongated members and/or planar members may be an elastomer. In other embodiments, typically ones requiring strength, the structural members may be metals, such as copper. In other embodiments, the structural members may be carbon. In other embodiments, the structural members may be ceramics, such as silica crystals, or glass. In still other embodiments the members may be any of proteins, carbohydrates, nucleic acid, or lipids. The materials selection of the elongated elements may be in part dictated by the method of manufacture and by the intended application, some of which are discussed herein below.

In certain embodiments, the elongated elements or planar members may be non-compressible elements. Alternatively, these structural members may be extensible elements, that is, capable of extension or an increase in length in response to application of a tensile

stress. Due to materials limitations, it is understood that such extensible properties will be experienced only over a limited range of motion. An extensible elongated element or planar member is expected to contract in length when compressed up to a certain point, at which point it will become non-compressible. Extensible members include but are not limited to linear (telescoping), curvilinear, helical, spring, sawtooth, crenulated or entanglement configurations. In other embodiments, the structural elements are made of rigid materials. Accordingly, the scaffold material of the present invention may be comprised of all non-compressible elements, all extensible elements, all rigid elements, or any combinations thereof.

In embodiments where some kinematic properties are desired or where some flexibility at interstices is desired, it may be desired to provide elongated elements or planar members having differing cross-sectional areas near or at the interstices or vertices. Thus, in one embodiment, the modules are comprised of elongated elements which are "thicker" at the center and "narrower" at the vertices to form a structure in which the junction of neighboring elongated members are less rigid than the elongated members. Similarly, in another embodiment the modules are comprised of planar members which are "thicker" at the center and "narrower" at the vertices to form a structure in which the junction of neighboring planar members are less rigid than the elongated members. In certain embodiments, the material properties of the scaffold material may be varied to provide increased compliance in the regions of the vertices, for example, by altering the cross-linking density of polymeric material.

It is well-established that arrangements of struts and/or planar members which satisfy Plateau's conditions exhibit high structural efficiency (Gibson *et al*, Cellular Solids: Structure & Properties, Pergamon Press, 1988). Stated another way, a very small amount of solid material can be used to achieve a truss of a desired strength, when that truss is arranged according to Plateau's conditions. This property has sometimes been exploited by hardening liquid foams in order to achieve a scaffold-like structure which satisfies these constraints. However, a truly monodisperse foam (for which every individual bubble of the foam has the same volume) cannot be achieved by this technique. Furthermore, no actual examples of perfectly regular scaffold materials are known to the inventors. Accordingly, prediction of the mechanical properties of such foams is complicated by their lack of symmetry.

According to the present invention, in order to achieve an "ideal" foam structure having a truly monodisperse structure, the inventors have used CAD/CAM techniques to produce lattices of polyhedra with translational symmetry. Particularly preferred foam structures are illustrated in Figs. 2-4, 6, 7, and 10-12, however any repeating pattern or combination of repeating patterns that can be created using CAD software may be fabricated with this method. In Figs. 2a and 2b, two views of an open-cell foam composed of elongated members integrally connected to form a body-centered cubic array of Kelvin's tetrakaidecahedra are shown. In Figs. 3a and 3b, two views of a closed-cell foam composed of substantially planar members integrally connected to form a body-centered cubic array of orthic tetrakaidecahedra. The substantially planar members define respective faces of the modules. The perfectly flat sides of the component polyhedra give this foam somewhat different mechanical properties relative to a foam satisfying Plateau's conditions, described above. Figs. 4a and 4b illustrate a hybrid foam as described above, having both closed-cell and open-cell elements.

Referring to Fig. 6, an octet truss, composed of regular octahedra tesselated to fill space, forms a particularly preferred type of open-cell foam structure. The structure includes integrally connected elongated members having edge lengths between 10^{-9} m and 1 m. In particular, octet trusses with edge lengths from 35 μm to 2 cm have been manufactured. The octet truss foam structure can be manufactured using any of the variety of materials discussed above. Particularly preferred materials include epoxy and acrylate resins, polyamide films, and metals (e.g. copper).

Repeating polyhedral foam structures, such as the octet truss, structure can be shaped into any variety of structures as required, such as planes, cylinders, cubes, cones, spheres, domes, egg-shapes, and any other form with complex curvature. In a particularly preferred structure as illustrated in Figs. 7-9, the octet truss is configured in the form of a cylinder surrounded by integrally connected inner and outer laminates. In another preferred structure as illustrated in Figs. 10-10A, the octet truss structure is configured in the form of an egg. In still another preferred shape as illustrated in Figs. 11-11A, the octet truss structure is configured in the form of a dome. In yet another preferred shape as illustrated in Fig. 12, the octet truss structure is configured in the form of a sphere.

In certain embodiments of the foam structures, such as the cylindrical structure of Fig. 8, the foam structures include a single scaffold layer. In other embodiments, the foam

includes multiple scaffold layers, such as shown in Figs. 7 and 9. It should be understood that the multiple octet layers are not exclusive to cylindrical shapes, and can be shaped into any form, as described above. The number of layers is determined, in part, by the requirements of the foam's application.

In certain embodiments, the foam structures may include laminates that are integrally connected to its surfaces or separately connected to its surfaces (e.g. by fixing, adhering, welding, and the like). Though laminates may be used in conjunction with any of the above-described scaffold materials, laminated cylindrical octet foam structures, such as illustrated in Figs. 7-9, are particularly preferred. Furthermore, the foam structures may include laminates on the outer surface, the inner surface, and on surfaces between multiple scaffold layers.

Amongst other advantages, the laminates enhance certain mechanical properties, such as stiffness of the structure, and prevent the permeability of liquid or gas in a radial direction. In one of many possible uses of the laminated cylindrical foam structures, a coolant may be allowed to flow through the truss structure so that the overall structure can be used as a radiator and/or insulator. In another example, the cylindrical structure may be used to provide counter current fluid flow, with a first fluid traveling in one direction through the cylinder and a second fluid, which may be the same or different from the first fluid traveling in an opposite direction through the truss structure. In another example, the laminated cylindrical structure is used as a load-bearing strut, such as a supporting pole.

The laminated truss structures may also be used as parts (e.g. wing coverings, exhaust pipes, inflow jets, the hull or fuselage, missile bay doors, and the like) in aircrafts, spacecrafts, watercrafts (e.g. surface ships, submersibles, and the like), as well as landcrafts (e.g. trucks, automobiles, buses, trains, tractor, cranes, and the like). Furthermore, the laminated truss structure can be used as high impact material coverings to protect any of the above-described crafts or buildings against damage from impacts, such as damage from exploding projectiles. One advantage of the laminated truss structure is that it maintains the structural integrity of the part due to its excellent mechanical properties, yet may also be used to perform other functions. For example when used to form the hull of a submersible watercraft, the void space of the foam structure can be used as a ballast tank to be filled and emptied to make the submersible sink and rise, which would increase the payload capacity of the vessel. This void space, in certain cases, could also be used to store fuel for the covert refueling of aircrafts, spacecrafts, watercrafts or landcrafts, or to store energy by creating high

surface area batteries in these spaces, or to pass electrical, optical, gas or hydraulic lines through the craft. The structure could also be configured to absorb acoustical energy by loading or filling the interstitial foam structure with sound absorbing materials, thereby making it effectively invisible to sonar. Further, if the hull of the vessel is constructed of the foam material, a fluid can be internally circulated throughout the hull to regulate its temperature. The temperature control permits matching to the external temperature of, for example, the water, to eliminate the vessel's thermal signature, or to cool the contents of the vessel as would be desirable if the vessel carried a liquefied gas. An internally circulating fluid would also redistribute a concussive force across the hull which would reduce the acoustic signature of the vessel. Furthermore, truss structures formed from, and subsequently filled with transparent materials, could function as windows having a high structural integrity.

The foam materials of the invention may also be useful for biomedical applications, and particularly in tissue engineering. For example, foams, such as the octet truss, with pore sizes on the dimension of 200 to 600 microns created from biocompatible and biodegradable polymers (e.g. polypropylene fumarate), biocompatible ceramics, bioglasses, or biocompatible metals (e.g. titanium), are outstanding scaffolds for bone repair and regeneration. These scaffolds may be coated with osteoinductive molecules or impregnated with hydroxyapatite crystals to further accelerate bone tissue ingrowth. Advantages provided over existing bone replacement materials include an immediate ability to bear physiological mechanical loads, increased energy dissipation, decreased stress-shield, and greatly enhanced tissue integration.

The porous foam materials of the invention have many additional and varied applications further to those described above. Such additional applications include but are not limited to substrates for chemical and biochemical catalysis, filtration, combustion devices, bearing housings, shrouds for jet engines, oil rig supports, amongst many others. In particular, many applications which currently use hardened foams for structural purposes could benefit from the structure of the present invention, since the idealized foam-like lattices described herein have more reproducible structure and higher structural efficiency than conventional foams. The very wide range of porosities and cell sizes achievable allows the properties of the foam to be precisely tailored to the desired application.

The above-described structures can be produced using a variety of computer-aided manufacturing techniques, as known in the art, including stereolithography, micromolding,

three dimensional microprinting, three dimensional laser-based drilling or etching, sintering, and fused deposition modeling. These techniques allow precise control over the structure of the finished material. These techniques may also be used to form dies which, in some embodiments, are assembled to form molds or other apparati for producing the foam structures. Alternatively, foams may be created using self-assembly techniques or sintering of regular particulates or crystals, as described further below.

The scaffold structure can be formed using molds or dies using any of a number of known techniques, such as casting, die casting, injection molding, reaction injection molding, and lost-core powder injection molding. These techniques have the common feature that the mold cavity is filled with a liquid composition which is then transformed into a solid structure. (The term "liquid composition," in this context, is considered to include all flowable compositions which can be used to fill a tortuous mold.) The most suitable technique for any given application will depend on the materials and geometry used. As described above, the scaffold structures can be manufactured from a wide variety of materials, including epoxies, thermoplastic polymers, thermosetting polymers, elastomers, metals, metal alloys, ceramics, biological materials, carbon, calcium, metalloids, and combinations thereof. Figs 8-12 show examples of foams fabricated in this manner using a master created with stereolithography that was then transformed into a copper metal structure using investment casting.

Because of the tortuosity of the mold, it will often be desirable to fill the mold cavity with the assistance of a pressure gradient. This may be accomplished by vacuum filling or by pressure casting, for example.

Once the negative mold has been filled, the liquid composition is solidified to form the structure. This may be accomplished in a variety of ways, *e.g.*, by simple cooling, as in classical injection molding and casting, by polymerization or other chemical reaction as in reaction injection molding (RIM), or by heating and sintering. The truss structure may be formed as a green preform at this stage, which will be transformed into the final structure after removal of the disposable negative-mold.

Fig. 13 shows an example of how these foams may be created using lost core molding. A negative mold 20 is used to form the curved foam shapes (e.g. cylindrical) illustrated in Figs. 7-12. Mold 20 includes a first die 22 and a second die 24 having respective patterns, that when assembled, form a mold cavity to produce the desired lattice structure. In the

embodiment illustrated, the first die 22 and second die 24 have curved surfaces to form a correspondingly curved foam structure.

After the liquid composition has been solidified, at least to a point where it is capable of maintaining its own structural integrity, the mold may be removed. The exact method of removal will depend on the material of the disposable dies from which the mold is formed, as well as the truss material. Materials for investment casting and similar techniques requiring a disposable mold are well known in the art, as are their methods of removal. For example, dies formed from a eutectic or other low-melting-point metal may be melted out of the structure. The metal should be chosen to have a melting point low enough that the solidified truss can maintain its structural integrity during melting of the mold. This technique is also suitable for removing dies formed from thermoplastic polymers and other organic and inorganic compositions capable of melting.

When the dies are formed, for example, from camphor, phosphorus, sulphur, or other materials capable of subliming, the dies may be removed by heating to the sublimation temperature. Material may be expeditiously removed even below the sublimation temperature by holding at a temperature where the die material has a significant vapor pressure, and pulling a vacuum or blowing gas through the system.

In yet another embodiment, the dies may be formed from a lightly sintered powder, nano- or micro-beads, crystals or the like, which can be disintegrated by mechanical action, for example by vibration at a resonant frequency of the powder, or by chemical dissolution. Vibration may also be used to disintegrate lightly bound crystals, such as slightly moistened salt crystals. In a further embodiment, the dies may be formed from a protein such as collagen, starch, or another material removable by enzymatic degradation.

Once the dies have been removed, what remains is a solidified regular truss. This may be the final product of the process, or may be subject to further sintering, surface treatments, or other processing. Thus, one aspect of the present invention is that it provides a method of cheaply producing such trusses, which have not previously been made by casting or molding processes, without the use of fasteners or connectors.

In yet another embodiment, the foams structures can be produced without molds using self-assembly techniques. In an example of such a technique, a plurality of spherical beads self-assemble to form a close packed structure with voids between the beads. The beads can be made of any suitable material, and in particular silica, and can be have diameters on the

order of nanometers to meters. The beads are sintered together and impregnated with any of the above-described scaffold materials which flows into the voids. After the scaffold material solidifies, the spherical beads are dissolved or disintegrated to yield the foam structure.

In another specific example of an industrial application of the lattice material of the present invention, the lattice material may be incorporated into a pattern for shell investment casting. In this embodiment, a pattern is constructed which has a porous foam structure such as any of the embodiments described above. In certain embodiments, the pattern further includes a thin, solid outer surface supported by the porous foam structure. The outer surface may be formed using the same process which is used to form the foam, or may be added after forming the scaffold, for example by wrapping a flexible material around a shaped foam. As explained above, the foams of the invention exhibit very high structural efficiency, and thus, use a minimal amount of material to support the outer shell.

Once formed, the surface of the pattern is coated with a hardenable material to form a shell coating. In one embodiment, the hardenable material may be a ceramic slurry which is cured to form a ceramic mold. The foam pattern is then eliminated by a method such as flash firing, leaving behind a shell suitable for casting metal or polymer parts in the shape of the original pattern. Techniques of forming a shell mold from a pattern for subsequent casting are well-known in the art, and are described in "Investment Casting," *Encyc. of Mat. Sci. & Eng.* Vol. 3, pp. 2398-2402 (1986) and Stereolithography and other RP&M Technologies, Society of Manufacturing Engineers, pp. 183-185 (1996). An advantage of incorporating the types of scaffold material described herein into an investment casting pattern is that the amount of material necessary to support the shell mold is reduced, compared to conventional hardened foam patterns, thereby reducing the amount of ash which is generated in the flash firing of the foam.

In a related embodiment, a similar pattern may be used to make a mold for sintering. In this embodiment, the pattern is used to produce a shell by forming a hardenable material around the pattern as in the previous embodiment described above. In addition, once the pattern has been removed as described above, the shell can be filled with a powder and subjected to high temperature and/or high pressure to sinter the powder to produce a solid article, according to techniques that are well-known in the art. The shell may be removed after sintering or may form a part of the final article. Descriptions of such well-known sintering fundamentals can be found, for example, in "Sintering of Ceramics," *Encyc. of Mat.*

Sci. & Eng. Vol. 6, pp. 4455-4456 (1986) and "Physical Fundamentals of Consolidation," *Metals Handbook*, 9th ed. Vol. 7, pp. 308-321.

The following examples illustrate additional embodiments of scaffold structures of the invention.

Example 1 - Octet truss

A relatively large octet truss, as generally described above and illustrated in Fig. 6, having edges of length 2 cm and width 2 mm, was fabricated via stereolithography from epoxy resin. In this technique, a computer simulation of the desired structure was constructed, and a liquid polymer resin was selectively polymerized (solidified) by a laser beam under the control of the computer to construct a polymeric material with 3D microstructural features that precisely match those specified using computer-aided design (CAD). The construction process involved fabrication of sequential thin cross section layers (analogous to tomographic sections), one being polymerized atop the other, until the entire 3D material was completed. Using this approach, 3D porous polymer networks can be fabricated with any microstructure that can be created using CAD. Although epoxy-based resins are most commonly used in this technique, in theory, any chemical that may be polymerized using a UV-sensitive initiator may be utilized.

A much finer truss has been constructed of polyimide via computer-controlled laser drilling. Once again, a computer simulation of the desired structure was first constructed, and then the simulation was used to guide a laser which drilled holes in a polyimide film. The resulting octet truss had struts of length 35 μm and width 2 μm.

Example 2 - Orthic tetrakaidecahedral lattice

Several open-cell foams in the shape of an array of orthic tetrahedra have been manufactured from epoxy resin. The length of the struts making up the trusses ranged from 4 to 7 mm, with widths of 400 to 700 μm. (All struts had a 10:1 aspect ratio). These foams were manufactured by stereolithography as described in Example 1.

Example 3 - Kelvin tetrakaidecahedral lattice

Open-cell foams in the shape of an array of Kelvin tetrahedra have been manufactured from epoxy resin as described in Example 1. Again, strut lengths were in the range of 5 to 7 mm, and strut aspect ratios were 10:1.

Example 4 - Weaire-Phelan lattice

An open- or closed-cell foam in the shape of a Weaire-Phelan foam may be constructed according to the techniques of Example 1. Stereolithography can be used to produce almost any shape which can be constructed using CAD techniques, including the Weaire-Phelan foam and other theoretically calculated repeating structures with even larger unit cells.

Example 5 - Flexible lattice

A structure having variable flexibility, such that the joints of the struts and/or planes making up the structure are more flexible than the members themselves, could be constructed by a number of techniques. For example, such structures have been produced out of flexible silicone rubber using a lost core molding technique. Using stereolithography as described in Example 2, the struts could be made narrower at their ends, causing the lattice to have increased flexibility. (In contrast, conventionally constructed foams have greater thicknesses of matrix material at these positions). Alternatively, techniques such as fused deposition modeling or three-dimensional microprinting could be used to construct a lattice having different material properties at the joints than in the centers of the struts.

A lattice with such flexible joints would be extremely compressible, while still being able to return to its original configuration. Such a structure might have utility, for example, in acoustic insulation, where it could be forced through a small aperture in a wall or the like, then expanding to fill a larger hollow space therein. This type of foam also may be used in body surface coverings such as feminine hygiene pads or diapers, in combination with absorbent materials to create body-hugging absorbent pads. Similar foams made of biocompatible and biodegradable materials, such as polymers or biological molecules, may be very useful as space-filling scaffolds for repair of surgical defects, wound healing, or tissue engineering.

Other embodiments of the invention will be apparent to those skilled in the art from a consideration of the specification or practice of the invention disclosed herein. It is intended

that the specification and examples be considered as exemplary only, with the true scope and spirit of the invention being indicated by the following claims.

What is claimed is:

Claims

1. A scaffold material, comprising:

an arrangement of integrally connected polyhedral modules which fill a three-dimensional space in a repeating pattern, each polyhedral module comprising a plurality of integrally connected structural members, and having edges of lengths in a range from 10^{-9} m to 1 m.

2. The scaffold material of claim 1, wherein the edges have lengths in a range from 10^{-6} m to 5×10^{-1} m.

3. The scaffold material of claim 1, wherein the edges have lengths in a range from 10^{-5} m to 10^{-1} m.

4. The scaffold material of claim 1, wherein the structural members comprise elongated members, integrally connected to define the edges of the polyhedral modules.

5. The scaffold material of claim 1, wherein the structural members comprise substantially planar members integrally connected to define faces of the polyhedral modules.

6. The scaffold material of claim 5, wherein neighboring polyhedral modules share substantially planar members as common faces.

7. The scaffold material of claim 5, wherein at least a portion of the polyhedral modules have at least eight faces.

8. The scaffold material of claim 1, wherein the integrally connected structural members comprise a closed-cell foam.

9. The scaffold material of claim 1, wherein the integrally connected structural members comprise an open-cell foam.

10. The scaffold material of claim 1, wherein the integrally connected structural members comprise a hybrid foam including open foam cells and closed foam cells.

11. The scaffold material of claim 1, wherein the structural members include an extensible material.

12. The scaffold material of claim 1, wherein the structural members include a non-compressible material.

13. The scaffold material of claim 1, wherein the structural members include a rigid material.

14. The scaffold material of claim 1, wherein at least one structural member is selected from the group consisting of linear, curvilinear, helical, spring, sawtooth form, crenulated, and entanglement elements.

15. The scaffold material of claim 1, wherein junctions of neighboring structural members are less rigid than the elongated members.

16. The scaffold material of claim 1, wherein at least a portion of the polyhedral modules are shaped as truncated octahedra having six quadrilateral faces and eight hexagonal faces.

17. The scaffold material of claim 16, wherein the truncated octahedra are orthic tetrakaidecahedra.

18. The scaffold material of claim 1, wherein at least a portion of the polyhedral modules are shaped as Kelvin tetrakaidecahedra.

19. The scaffold material of claim 1, wherein the polyhedral modules are arranged as a Weaire-Phelan foam.

20. The scaffold material of claim 1, wherein all of the polyhedral modules are of the same volume.

21. The scaffold material of claim 1, wherein the structural members comprise at least one of the group consisting of polyacrylates, polyepoxides, polyesters, polyurethanes, poly(methacrylic acid), poly(acrylic acid), polyimides, polysiloxanes, poly(glycolic acid), poly(lactic acid), polyamides, metals, glasses, ceramics, carbon, proteins, carbohydrates, nucleic acids, and lipids.

22. The scaffold material of claim 1, wherein the scaffold material is fabricated using computer-aided manufacturing techniques.

23. The scaffold material of claim 22, wherein the computer-aided manufacturing techniques are at least one of stereolithography, micromolding, three dimensional microprinting, three dimensional laser-based drilling or etching, self-assembly techniques, sintering, lost core molding, and fused deposition modeling.

24. The scaffold material of claim 1, wherein the arrangement comprises a plane.

25. The scaffold material of claim 1, wherein the arrangement comprises a non-planar shape.

26. The scaffold material of claim 25, wherein the arrangement of polyhedral modules comprises a cylinder.

27. The scaffold material of claim 25, wherein the arrangement of polyhedral modules comprises an egg.

28. The scaffold material of claim 25, wherein the arrangement of polyhedral modules comprises a dome.

29. The scaffold material of claim 1, wherein the arrangement of polyhedral modules comprises a sphere.

30. The scaffold material of claim 1, further comprising a laminate on at least a portion of a surface of the scaffold material.

31. The scaffold material of claim 30, wherein the laminate is integrally connected to the portion of the surface of the scaffold material.

32. The scaffold material of claim 30, wherein the laminate is separately connected to the portion of the surface of the scaffold material.

33. The scaffold material of claim 1, wherein the scaffold material is used as part of a seacraft.

34. The scaffold material of claim 1, wherein the scaffold material is used as part of a spacecraft.

35. The scaffold material of claim 1, wherein the scaffold material is used as part of an aircraft.

36. The scaffold material of claim 1, wherein the scaffold material is used as part of a landcraft.

37. The scaffold material of claim 1, wherein the scaffold material is used in biomedical applications.

38. The scaffold material of claim 37, wherein the scaffold material is used in tissue replacements.

39. The scaffold material in claim 1, wherein the scaffold material is used in catalysis or biocatalysis systems.

40. A method of manufacturing a mold for a foam article, comprising:

(a) providing a pattern comprising a scaffold material including an arrangement of polyhedral modules which fill a three-dimensional space in a repeating pattern, each module being comprising a plurality of structural members, and having edges of lengths in a range from 10^{-9} m to 1 m,

(b) coating the pattern with a hardenable material,

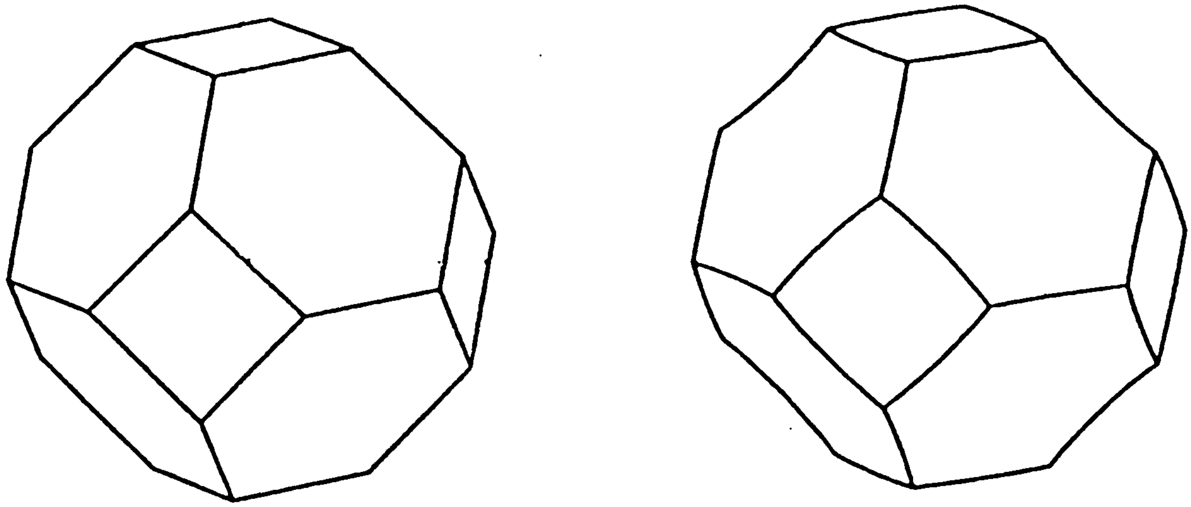
(c) transforming the hardenable material into a hard shell mold, and

(d) removing the pattern from the hard shell mold.

41. The method of claim 40, wherein the pattern further comprises a solid outer surface surrounding the scaffold material

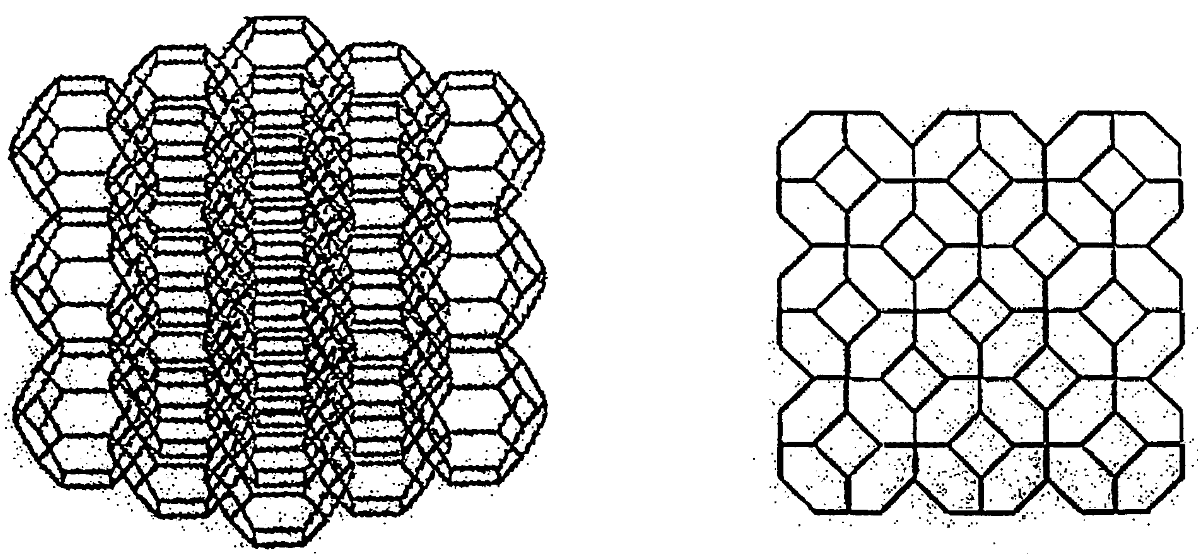
42. The method of claim 40, further comprising filling the hard shell mold with a flowable material and cooling the flowable material to form an article.

43. The method of claim 42, wherein the article comprise at least one of the group consisting of polyacrylates, polyepoxides, polyesters, polyurethanes, poly(methacrylic acid), poly(acrylic acid), polyimides, polysiloxanes, poly(glycolic acid), poly(lactic acid), polyamides, metals, glasses, ceramics, carbon, proteins, carbohydrates, nucleic acids, and lipids.



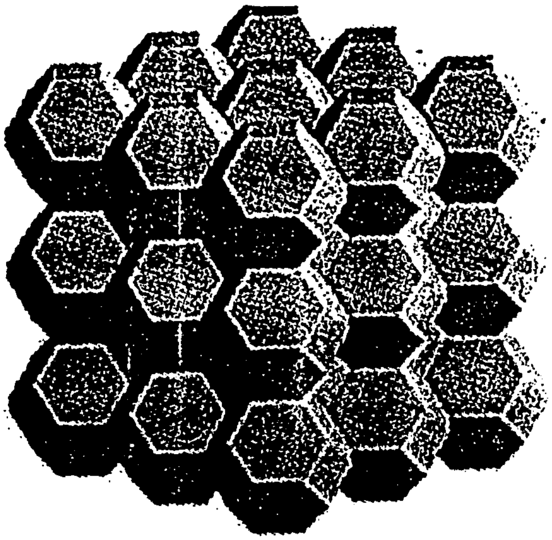
(a) (b)

Figure 1



(a) (b)

Figure 2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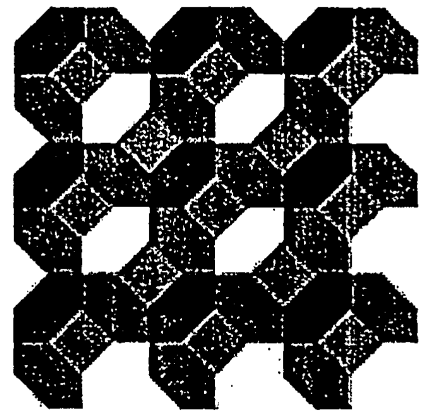
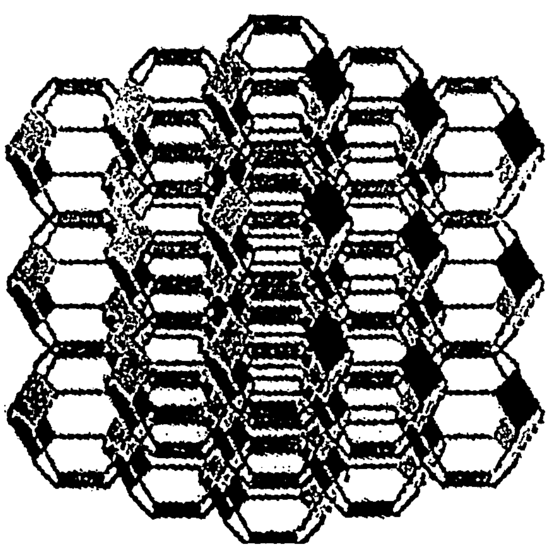

(b)

Figure 3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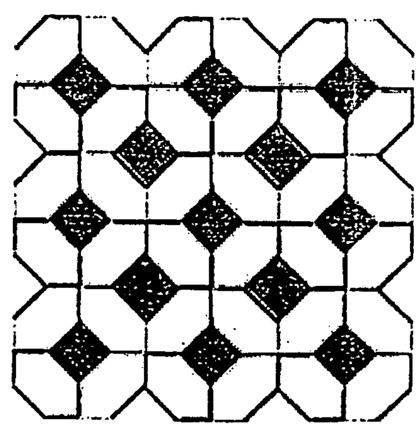
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Figure 4

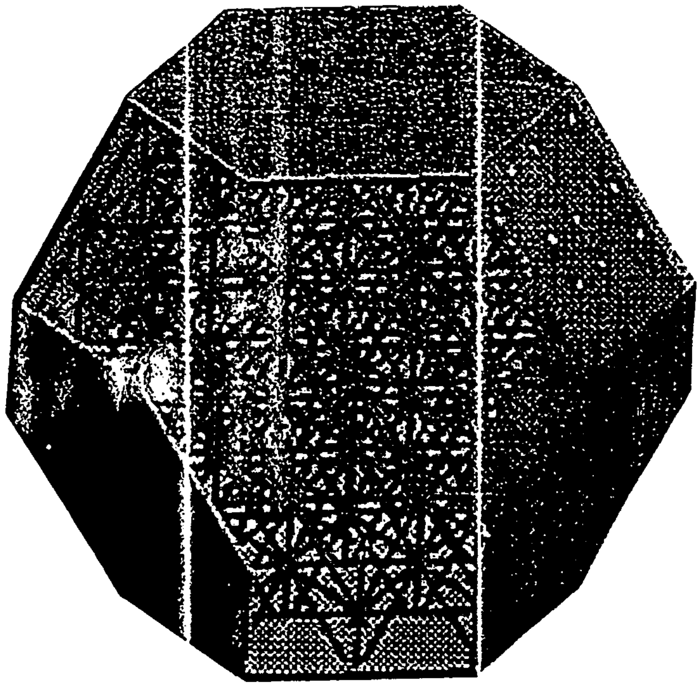


Figure 5

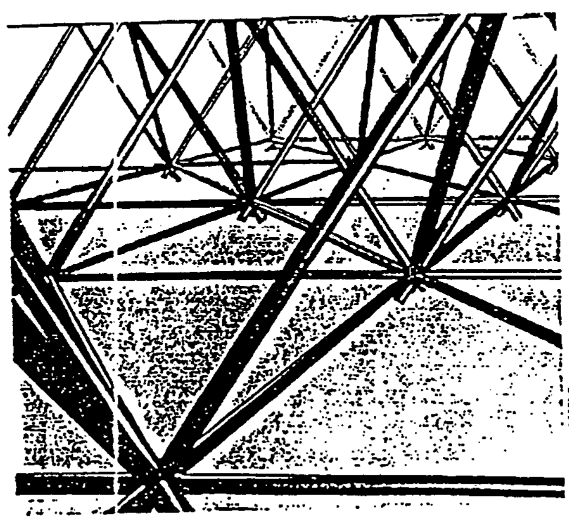


Figure 6

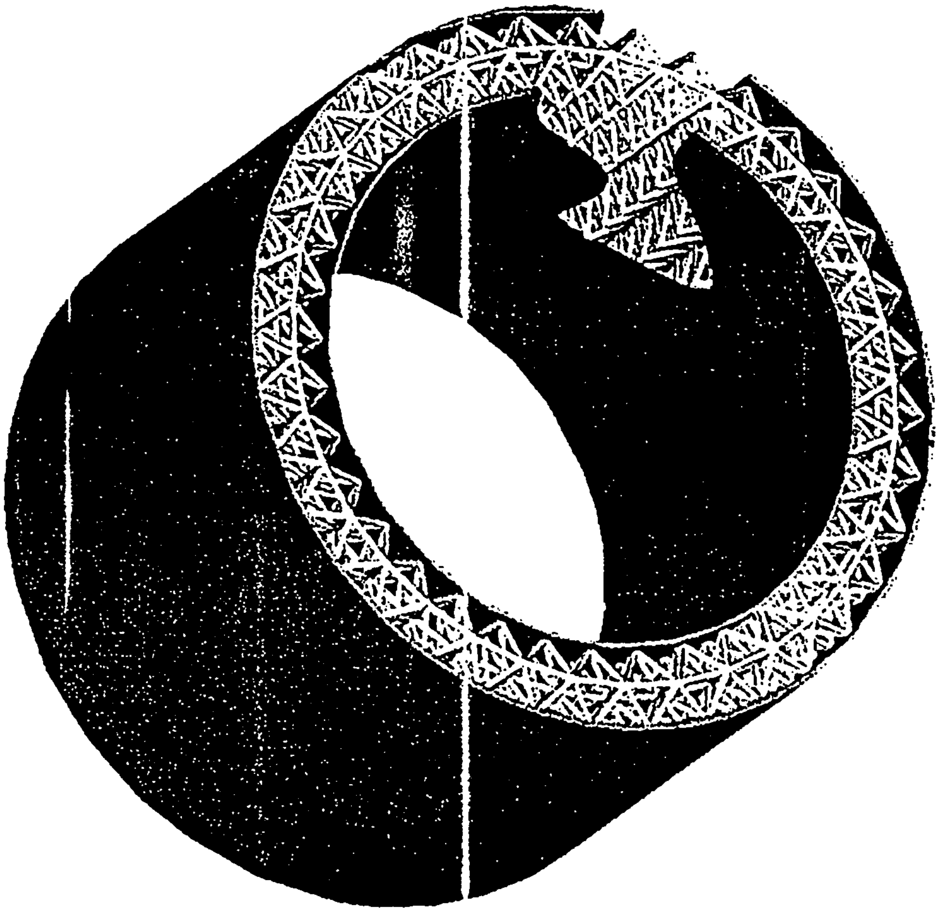


Figure 7

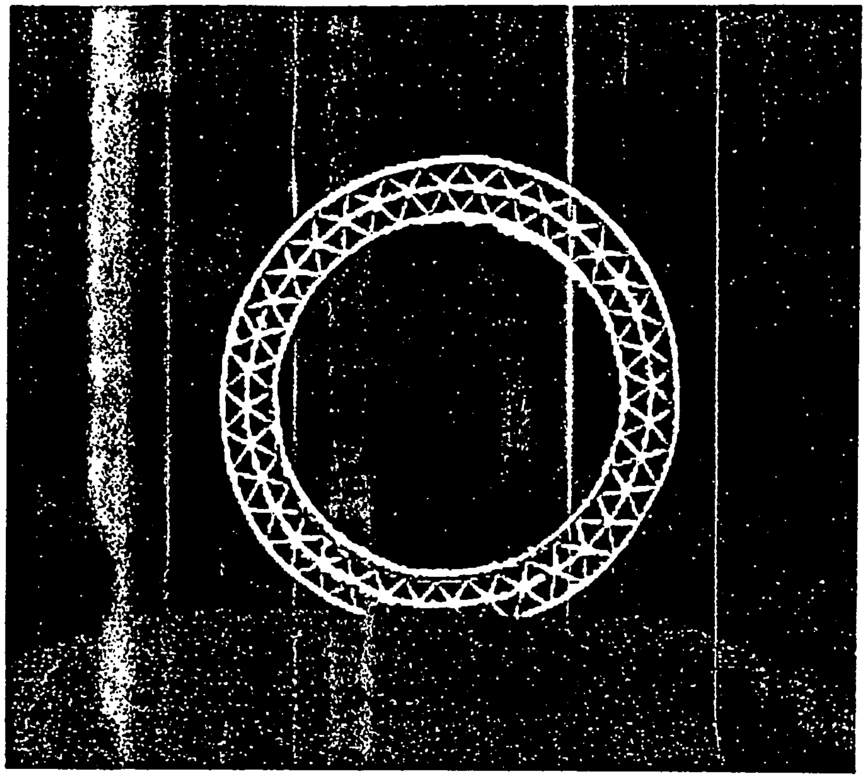


Figure 9

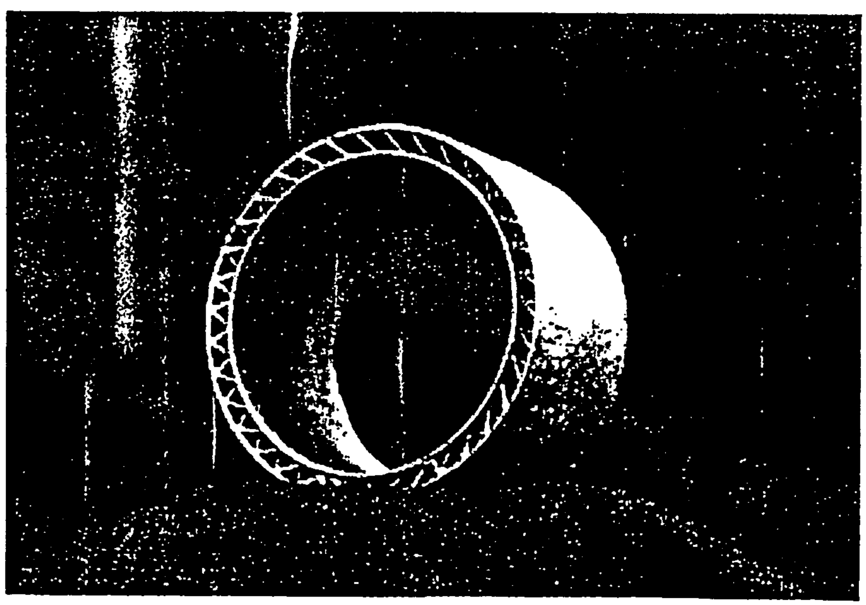


Figure 8

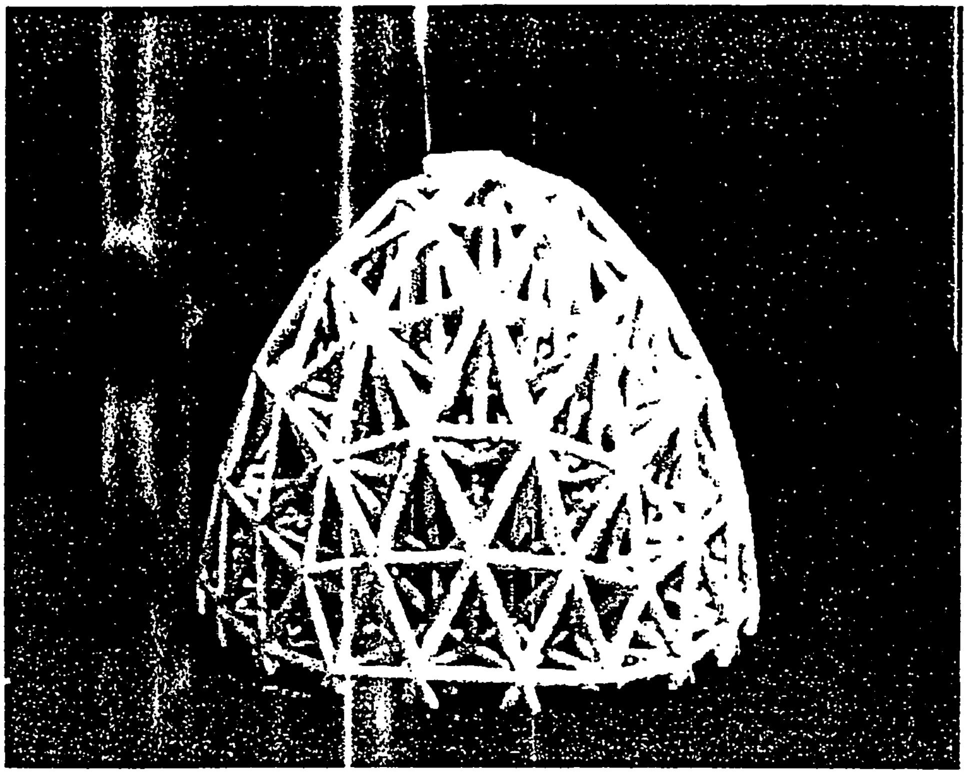


Figure 10

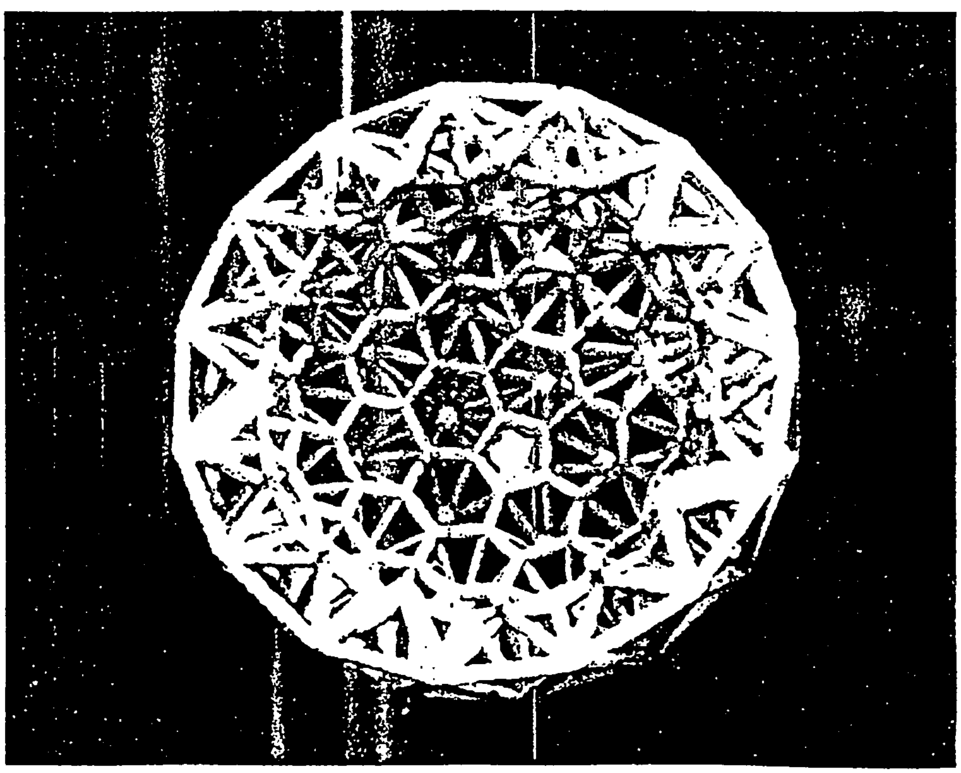


Figure 10A

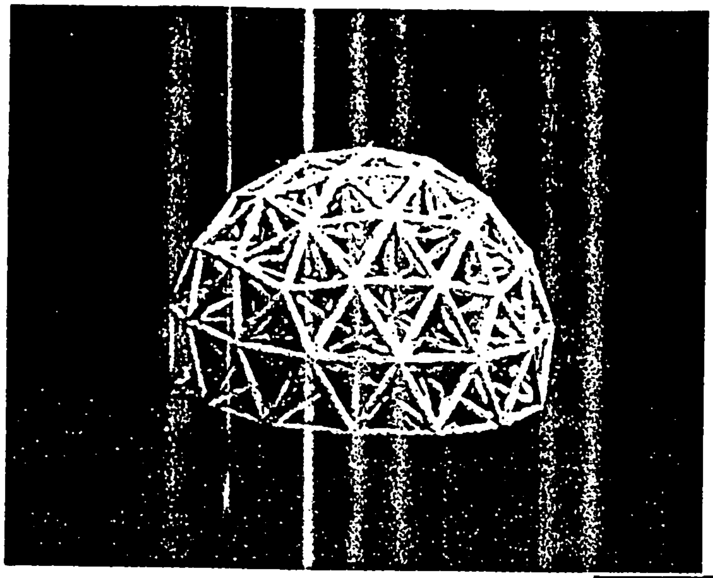
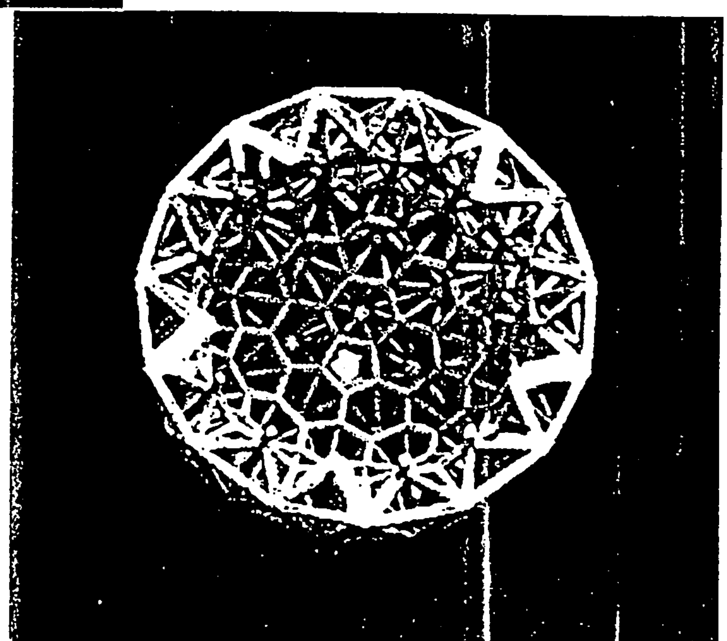


Figure 11

Figure 11A



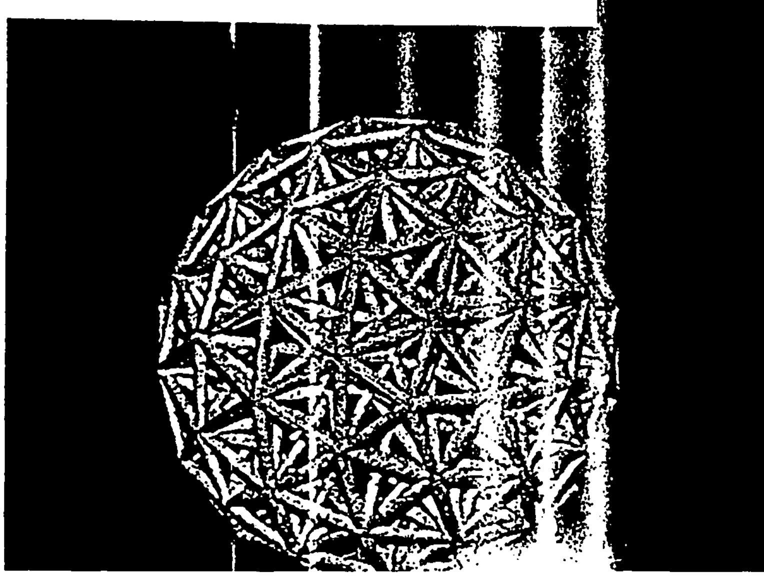


Figure 12

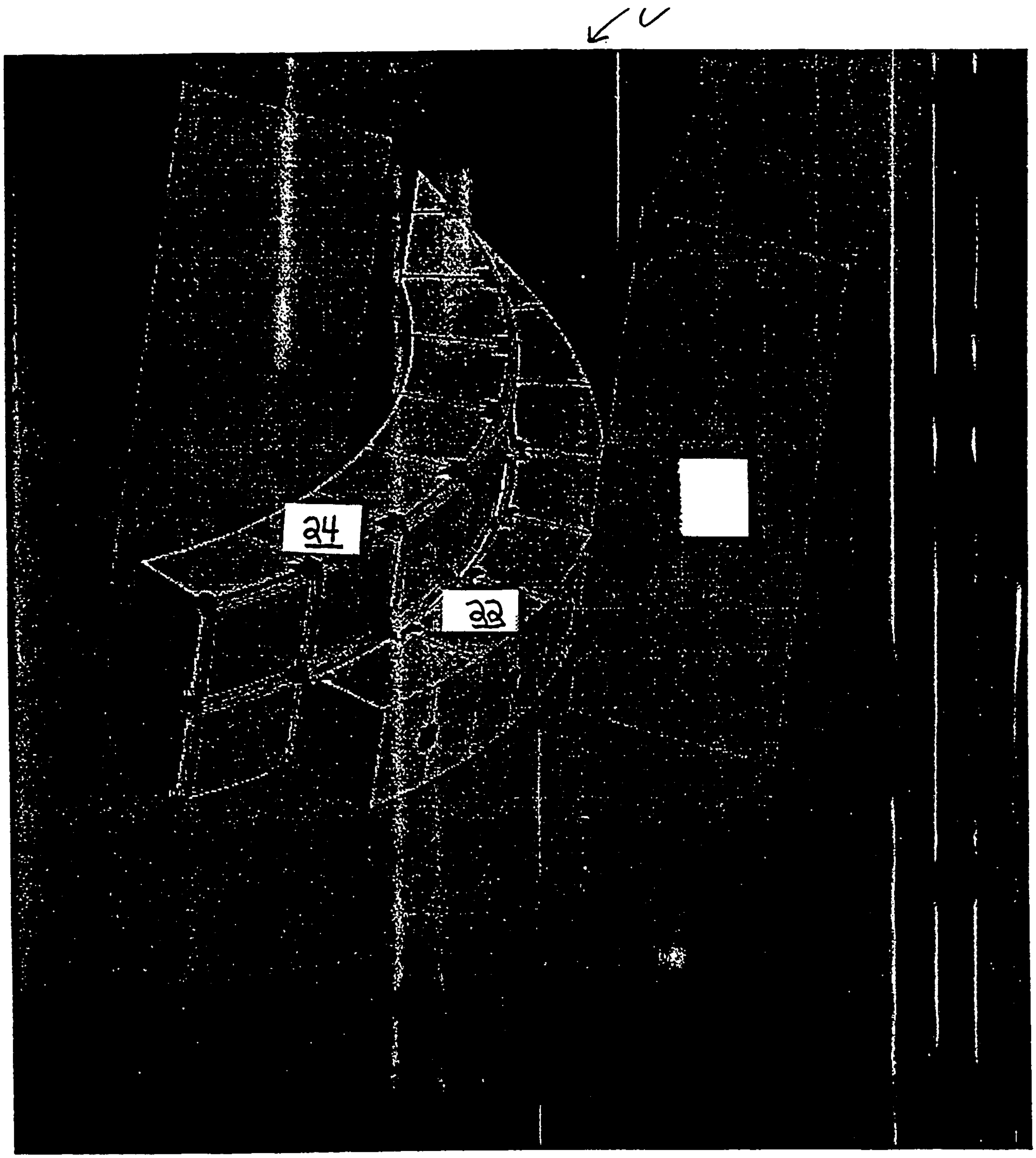


Figure 13

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/27397

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B29C67/00 C08J9/00 A61L27/00 B29C33/38

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B29C G09B E04B F16S A61L C08J B01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 025 200 A (W.R. POWERS) 13 March 1962	1-7,9, 11,14, 21,24,25
Y	see the whole document	33-36
Y	US 5 208 271 A (GALLAGHER JAMES A) 4 May 1993 see column 8, line 42 - line 52	33-36
P,X	WO 98 02382 A (STANKIEWICZ EDWIN ;ULTRAMET (US)) 22 January 1998 see the whole document	1-7,9, 12-14, 21,29

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 April 1999	21/05/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Mathey, X

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 649 691 A (TEXAS INSTRUMENTS INC) 26 April 1995 see the whole document	1-7, 12-14, 20-25, 40-43
X	D. WEAIRE & R. PHELAN: "A counter-example to Kelvin's conjecture on minimal surfaces" PHIOSOPHICAL MAGAZINE LETTERS, vol. 69, no. 2, 1994, pages 107-110, XP002101227 cited in the application see the whole document	16-19,29
X	US 3 637 458 A (PARRISH ROBERT GUY) 25 January 1972 see column 1; claims	1-8,11, 14,21,24
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X	GB 858 127 A (SCOTT PAPER COMPANY) 4 January 1961	1-7,9, 11,14, 21,25, 29,39
Y	see page 3, line 3; claims 1,5,11; figures	24,26-28
P,Y	WO 98 05304 A (LI REBECCA ;CYTOTHERAPEUTICS INC (US); HAZLETT TYRONE F (US)) 12 February 1998 see page 10; claims	24,26-28
X	JP 09 166286 A (KAJIKAWA TAIJI) 24 June 1997 see figures	1-7, 11-14, 16,17, 28,30,32

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern nal Application No
PCT/US 98/27397

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